Pulsar/Supernova Remnant Associations

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Abstract. We list and review proposed pulsar/supernova remnant associations, summarize recent highlights in the field, including searches for young pulsars, searches for remnants, recent studies of previously proposed associations, and attempts at pulsar/remnant association syntheses. We argue that most proposed pulsar/supernova remnant associations require additional investigation before they can be considered secure, and we suggest directions for future work.

1. Introduction

No review of pulsar/supernova remnant (PSR/SNR) associations should begin without lavishing praise on Baade & Zwicky (1934), who hypothesized neutron stars are born in supernova explosions of massive stars, long before neutron stars had been discovered[1]. The discovery of the pulsar in the Crab nebula made the Baade & Zwicky hypothesis seem visionary; but after we finish scraping our amazed jaws off the floor, the task of putting such hypotheses to careful scientific scrutiny for general cases remains.

PSR/SNR associations, the subject of this review, can potentially prove the Baade & Zwicky hypothesis. Their study also has the potential to constrain the distribution of birth magnetic fields, birth spin periods, and space velocities of neutron stars, as well as pulsar beaming fractions. From the SNR point of view, associations help constrain remnant distances, ages, and elucidate unusual remnant morphology or evolution. This can be done by considering individual associations (§2., §3.3) or via population syntheses (§4.). The study of associations properly begins with the discovery of candidates; recent searches are summarized in §3.1. and §3.2.

In this review, the discussion is limited, somewhat arbitrarily, to SNR associations involving radio pulsars. Notable omissions are: SS433 and 1E2259+586, which are probably binary neutron stars in SNRs (Clark & Murdin 1978; Fahlman & Gregory 1981); probable pulsar-driven plerions and point sources in remnants from which pulsations have not been seen (e.g. Vasisht et al. 1996; Petre et al. 1996); and soft gamma repeaters (SGRs), which may be young neutron stars, as inferred by the presence of an SNR in the SGR error box (e.g. Kulkarni & Frail 1993).

[1] With similar vision, Wheeler (1966) suggested, before the discovery of the first rotation-powered neutron star, that the Crab SNR is powered by a neutron star's rotational energy.

2. Review of Proposed Associations

Table 1 presents a list of 28 proposed PSR/SNR associations. We have attempted to make the list complete, and any publication that suggests an association is possible has been included. Similar compilations can be found elsewhere (Caraveo 1993; Frail et al. 1994b; Gorham et al. 1996; Allakhverdiev et al. 1996). In the Table, the remnant type T is "P" for a plerion, "S" for a shell, and "C" for a composite, according to Green's catalog[2]. The pulsar distances are obtained from the dispersion measure and the Taylor & Cordes (1993) distance model, or from HI observations when available. The remnant distances are best estimates from the literature, in general from the $\Sigma - D$ relation or from apparent interactions with nearby objects. The pulsar ages are the characteristic ages (obtained assuming braking index $n = 3$ and initial spin period P_0 much less than the current spin period, P.) If $P_0 \simeq P$, the age is overestimated, while if $n < 3$, it is underestimated. Some age corroboration may be provided by the presence of timing noise and/or glitches. Remnant ages in the Table are the best available estimates from the literature, but in general are highly uncertain; they depend on the assumed phase of the shell expansion, the distance to the remnant, the energy of the explosion, and strongly on the typically unknown density of the ISM into which the explosion occurred. The parameter β is the angular pulsar displacement from the SNR centre (θ) in units of the SNR angular radius, and $v_t = d\theta/\tau$ is the implied pulsar transverse velocity, where we adopt the most conservative τ and d from columns 4 and 5 respectively. The column "G" is described below.

Proposed associations may be merely a result of coincidental projection of the pulsar and SNR on the sky. The probability of coincidental projection can be evaluated in a statistical way, by comparing the surface density of pulsars and SNRs in different parts of the Galaxy. Such considerations are not very useful in assessing any particular proposed association, but are crucial in PSR/SNR association syntheses discussed in §4. To objectively assess the evidence for each proposed association, as well as to illustrate the reasoning used in the literature in evaluating associations, we consider the following questions:

- **Do independent distance estimates agree?** In most cases, meaningful comparisons of the pulsar and remnant distances can be made. For example independent distance estimates for PSR B1853+01 and the W44 remnant are in good agreement, while for PSR B1758−23 and W28, they are in obvious disagreement. In a large number of cases, however, the strongest conclusion that can be made is that the distances do not disagree (e.g. PSR J1341−6220 and G308.8−0.1).

- **Do independent age estimates agree?** Remnant ages are difficult to estimate and so comparisons here are not usually constraining. One notable exception is PSR B1509−58 and MSH 15−52, for there which is clear disagreement (see §3.).

[2] http://www.phy.cam.ac.uk/www/research/ra/SNRs/snrs.data.html

- **Is the implied transverse velocity reasonable?** Here, instead of asking if the pulsar is located within the remnant boundaries, we ask if the pulsar's implied transverse velocity, assuming its birth at the geometric remnant centre and the most conservative age estimate, is consistent with the Lyne & Lorimer (1994) velocity distribution, derived from proper motion studies. Note that identifying the remnant centre is often difficult.

- **Is there evidence for any interaction between the pulsar and SNR?** Although this question is subjective, associations have been proposed on the basis of morphological evidence only (Shull et al. 1989; Kundt & Chang 1992); pulsars have relativistic particle winds that likely "rejuvenate" SNRs via particle interaction with the SNR shock. However, a pulsar-driven synchrotron nebula is not necessarily related to a previous supernova (§3.1).

- **Does the proper motion vector of the pulsar point away from the remnant centre?** In general, young pulsar proper motions are best measured via interferometry, since timing parameters are usually contaminated by red noise and glitches. The direction of proper motion may also be inferred from the morphology of a pulsar wind nebulae (e.g. Cordes et al. 1993). A proper motion measurement has the potential to disprove an association regardless of the answers to the other questions.

The above questions can be used to classify each association according to how much evidence exists in its favor. Associations for which the answers to all questions are affirmative are secure, and are classified "group" 1; successively less secure associations as determined by the number of affirmative answers to the above questions are classified in increasing group number, with group 5 associations being unlikely. This classification scheme is meant as an objective, overall guide to the credibility of an association, but should not substitute for a detailed study in individual cases. The column "G" in Table 1 shows the classification for each proposed association. Note that associations in group 3 or 4 most often suffer from a lack of relevant observations, rather than evidence against the association. They should simply be considered uncertain.

Several conclusions can be drawn from inspection of Table 1. First, of the 28 proposed associations, only seven can be considered compelling, with only three of those certain. This is in strong contrast to other authors who have suggested that as many as 17 associations are probable. Indeed it is remarkable that of the 22 pulsars having characteristic ages under 100 kyr, 18 are included in the Table. (The exceptions are PSRs B1046–58, B1727–47, B1737–30, and B1916+14). However this may also simply be the effect of young pulsars being given preferential attention; we discuss this disagreement further in §4. Associations proposed since 1994 are indicated in the Table with an asterisk; three that have yet to be published have not been classified and are at the bottom. We note that no association that has been proposed since 1994 falls in either our group 1 or 2. If we consider only the most secure associations, i.e. those in groups 1 and 2, the mean pulsar transverse velocity v_t ~ 410 km/s. However, none of the proposed associations involving $v_t > 260$ km/s has been verified independently by a proper motion measurement. If PSR B1757–24, the "Swan/Duck" pulsar, is excluded from the estimate of the mean transverse velocity, we find

$\bar{v}_t$ ≈ 210 km/s, far less than previous estimates, and indeed less than the mean pulsar transverse velocity (Lyne & Lorimer 19$)1). Thus, PSR/SNR associations do not unambiguously provide evidence for large pulsar velocities.

3. Recent Highlights

We now take a moment to consider highlights of recent work on particular PSR/SNR associations.

3.1. Searches for SNRs near Young Pulsars

One technique for finding new PSR/SNR associations is to search for extended radio emission near young pulsars. Recently, Frail et al. (1994b) made deep 20 and 90 cm VLA images of the fields near three young pulsars, PSRs B1643–43, B1727–33, and B1706–44. They found extended emission around all three, and argue that all three represent PSR/SNR associations. Images of the field around PSR B1643–43 reveal an arc of emission consistent with a partial shell morphology. The coincidence of the partial shell with the pulsar position suggests an interaction, and is consistent with the pulsar's motion away from the approximate geometric remnant centre. Images of the field near PSR B1727–33 reveal emission near the pulsar that extends mainly northward. Its interpretation in terms of an SNR is problematic in this case, as unlike that for PSR B 1643–43, the morphology of the "partial shell" is inconsistent with the inferred motion of the pulsar. The emission may be pulsar-powered, but is not necessarily the remnant of a supernova explosion (see §4.). Extended emission near PSR B1706–44 was first detected by McAdam et al. (1993); Frail et al. (1994 b) confirm the detection. They discuss some problems with an association, namely the absence of any interaction despite this pulsar's particularly large spin-down luminosity.

3.2, Searches for Young Pulsars near SNRs

Although historically many young pulsars later plausibly associated with SNRs have been discovered in untargeted searches (e.g. Damashek et al. 1978; Clifton & Lyne 1986; Johnston et al. 1992), the success of a search targeting SNRs by Manchester et al (1985) made similar, more sensitive searches attractive. Recent searches for pulsars in the direction of SNRs have met limited success. Gorham et al. (1996) searched for radio pulsations from 18 supernova remnants using the Arecibo telescope but found no new pulsars. Biggs & Lyne (1996) searched 29 SNRs at Jodrell Bank, but found no new pulsars. Kaspi et al. (1996a) searched 40 Galactic remnants, and found two new pulsars, one of which is almost certainly not associated with its target remnant. The other, PSR J1627–4850, is at a position well within the remnant boundaries, and distance estimates to the two agree, but the pulsar characteristic age is well over the expected lifetime of SNRs. The association is plausible under the controversial hypothesis that pulsars can be born with relatively long spin periods.

3.3. New Results on Previously Proposed Associations

Vela: Addressing previous concerns (Bignami & Caraveo 1988) regarding the association of the Vela pulsar with the Vela SNR, Aschenbach et al. (1995), ot)-

tained a ROSAT image of the Vela SNR. They project the apparent trajectories of six extended features outside the remnant backward, and, with the known pulsar proper motion, find a consistent origin for all objects, the location of the supernova. They estimate the explosion occurred ~18 kyr ago, though larger ages are also consistent. Independently, from timing, Lyne et al. (1996) conclude the age of the pulsar is greater than its characteristic age of 11 kyr, because of evidence for a surprisingly small braking index, $n = 1.3$. They further point out that if such small braking indexes are standard for Vela-like pulsars, their transverse velocities implied by possible SNR associations are overestimated.

PSR B1509−58: Although PSR B1509−58 and its surroundings have recently been studied in detail, in contrast to Vela, this association is not yet clear. The region is complex, and the large radio SNR, MSH 15−52, appears to be much older than the pulsar (Seward et al. 1983); evidence suggests MSH 15−52 is not associated with the pulsar, and that the system comprises more than one remnant. A proper motion limit for the pulsar (Kaspi et al. 1994) makes an association with the large radio SNR MSH 15−52 difficult; additional evidence against it is presented by Strom (1994) and Du Plessis et al. (1995). However, the pulsar is almost certainly associated with some component of this complex system. Thorsett (1992) proposed that the "guest star" of 185 AD was the historical supernova that produced PSR B1509−58, which might have clarified the situation by establishing a firm age for the pulsar, however a recent rereading of the records suggests the guest star was a comet, not a supernova (Chin & Huang 1994).

PSR B1800−21: Kassim & Weiler (1990) proposed an association between the 134-ms pulsar PSR B1800−21 and SNR G8.7−0.1. This was problematic since an association implied an extremely large transverse velocity for the pulsar. Frail et al. (1994a) made new VLA images of the area that suggested the association is not real, since no remarkable emission was found near the pulsar. However, Finley & Ögelman (1994) observed the region using ROSAT and concluded an association is plausible if the supernova occurred near the present pulsar position, and expanded into a nearby molecular cloud.

4. Syntheses of PSR/SNR Associations

Here we discuss recent attempts at synthesizing the available data on PSR/SNR associations. They fall into two broad categories:

- **Optimistic:** Frail et al. (1994b), after finding extended emission near three young pulsars (see §3.1) and compiling a list of proposed PSR/SNR associations, conclude that of all young pulsars, "the majority are associated with supernova remnants." Their main argument is that a larger fraction of young pulsars has nearby extended emission compared with the general pulsar population. They cautiously suggest the number of associations is as high as 17, a conclusion also arrived at by Caraveo (1993). They find that $v_t \simeq 500$ km/s for young pulsars on the basis of the associations, and discuss the implications.

- **Pessimistic:** Gaensler & Johnston (1995b), using a creative Monte Carlo simulation, argue that most proposed associations are actually false. In their analysis, they seed the Galaxy with 35,000 supernovae, allowing every explosion to produce both a pulsar and a shell expanding independently into a warm or hot ISM. They then simulate untargeted 1 GHz radio surveys in order to discover SNRs, as well as targeted and untargeted radio pulsar searches. To model the pulsar population, they assume the Lyne & Lorimer (1994) for the velocity distribution, the Lorimer et al. (1993) pulsar luminosity function, the Biggs (1990) beaming law, and the Taylor & Cordes (1993) DM distance scattering model. They compare their simulation's "observed" PSR/SNR associations with those in the literature, and arrive at interesting conclusions: only $\sim 2\%$ of pulsars with $\tau < 25$ kyr should have $\beta > 1$, although $\sim 30\%$ of pulsars with $100 < \tau < 200$ kyr can have $\beta > 1$, in stark contrast to the percentages of the proposed PSR/SNR associations (Table 1). From their results, they conclude that only ~ 7 of those in Table 1 are real, although they cannot determine which.

The assessment of most PSR/SNR associations presented in this review is clearly less optimistic than that expressed by Frail et al. (1994b). We see several reasons for this. In some instances, though they find extended emission near young pulsars, its identification as a remnant is less clear. For example, the morphology of the emission near PSR B1727-33 is unlike other remnants; though it may be pulsar-driven, the evidence for it being the remnant of a supernova explosion is unclear. In general, the interpretation of extended emission is necessarily somewhat subjective; of interest might be a study of the chances of finding extended radio emission in *any* direction, given a deep VLA observation. In addition, if, as suggested by Shull et al. (1989), pulsars can "rejuvenate" remnant shells, SNRs containing fast pulsars may be preferentially easier to detect, estimates of large v_t may be artificially inflated, and at least some SNRs might not be observable without pulsar rejuvenation (cf. Braun et al. 1989).

Even considering the above uncertainties in the "optimistic" viewpoint, the conclusions of Gaensler & Johnston stand in striking opposition. We see a number of reasons for this. Several phenomena that may have important impacts on the discovery of new PSR/SNR associations were not modeled in their simulation. As discussed above, pulsars may "rejuvenate" shells, so the assumption that the pulsar and shell evolve independently may be incorrect. Second, Gaensler & Johnston simulated only untargeted searches for remnants, rather than the sorts of searches done by McAdam et al. (1993) and Frail et al. (1994b), which may reveal low surface brightness remnants. Third, X-ray contributions to this field were not considered even though two well-studied associations are direct results of X-ray discoveries (PSR B1509-58 and PSR B0540-69). Finally, in simulating searches for pulsars, Gaensler & Johnston made necessary, but uncertain, assumptions about the pulsar population and the evolution of remnants: their results are particularly sensitive to the filling factor of the different ISM phases, which governs the evolution of shells.

5. Conclusions

The study of PSR/SNR associations holds the key to many fundamental issues in neutron star astrophysics. Much progress has been made in recent years owing to tenacity and hard work; that the number of compelling associations is relatively small in spite of the effort is not intended to be discouragement for those workers, but rather inspiration for them and others to, in addition to proposing new associations, study those already proposed in more detail. In particular, young pulsar proper motion measurements have the potential to decide unequivocally if many of the associations listed in Table 1 are real or not, and therefore should be considered a top priority. Furthermore, careful synthesis analyses attempting to account for previously unmodeled factors, like those discussed at the end of §4., should also prove valuable.

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Table 1. I 'i opo-ed PSR/SNR Associations. Associations are arranged by gr oup, andby pulsar characteristic age within **each group,** Asterisks nc :xt to pulsar names indicate associations proposed since 1994. For other infor mation, see §2.

PSR	SNR	T	τ (kyr)	d (kpc)	β	v_t (km/s)	G	Refs
			PSR/SNR					
Im5"314 2"1	Crab	P	1.3/0.9	"2/2	~0	~0	--1	1 "
110540- 69	SNR0540- 69.3	P	1,7/0.(;	-/50	~0	~0	1	2
}10833- 45	Vela	C	11/18	0,6/0.5	0.3	120	1	3,4
J1341- 6220	G308.8- 0.1	C	12/32	8.7/7	0.35	600	2	5,6
111757-24	G5.4- 1.2	C	16/]4	4.6/5	1.2	1600	2	7,8
1)1853-I 01	W44	S	20/~10	3/3.1	0.6	250	2	9
B1951+32	CTB 80	C	10'//96	2.4/3	~0	300	2	10
111509-58	MSH 15- 52	C?	1.7/10	5.7/4.2	0.2	3000	3	11
}11800- 21	G8.7- 0.1	S	16/15-28	4/3,2- 4,3	~0	~0	3	12,13,14
1)1643- 43*	G341.2+0.9	S	33/.	6.9/8.3 9.7	0.7	500	3	15
B2334+61	G114.3+0.3	C	41/10 100	2.4/1.8	0.1	<50	3	16
1)175 8-23	W28	C	58/35 150	13.5/2	1.0	200	3	17,18
111610- 50*	Kes 32	S	7.5/5	7/3-7	1.5	1600	4	19,20
}11706- 44	G343.1- 2.3	S	1'/.5/.	2,4-3.2/3	1.0	800	4	21,15
111727- 33"	G354.1+0.1	?	26/-	4.2/-	~0	460	4	15
}11830- 08*	W41	S	148/<50	4 5/4.8	1.6	200	4	22
B1855+02	G35.6- 0.5	?	160/-	9/4 or 12	0.4	100	4	23
J1627-4845*	G335.2+0.1	S	2700/-	6.8/6.5	0.4	70	4	24
B1930+22	G57.3+1.2	?	40/-	9.6/4,5	0.5	750	5	25
B0611+22	IC 443	S	89/65	4.7/1.5	1.7	110	5	26
B0656+14	Monogem	S?	110/60 90	().8/0.3	0.5	200	5	27,28
B1832-06	G24.7+0.6	C	120/1')	6.3/4,4	1.6	360	5	22
J2043+2740'	Cygnus Loop	S	1 200/20	1.1/0.6	2.5	1500	5	29
111154- 62	G296.8- 0.3	S	1600/25	10/4	1.4	550	5	30
B0458+46	G160.9+2.6	S	Iwo/3[).100	1.8/1-4	0.3	<300	1	31,32
]11823- 13*	~	C	21/-	4.1/-	~0	~0	-	33
J1105-6107*	G290.1- 0.8	S	63/-	7/>4	2.9	650	-	34
J0538+2817*	S147	S	600/101)	1.6/1-1.6	0.4	30	-	35

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